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**AERODYNAMIC SHAPE OPTIMIZATION DIRECTED
TOWARD A SUPERSONIC TRANSPORT USING SENSITIVITY
ANALYSIS**

By

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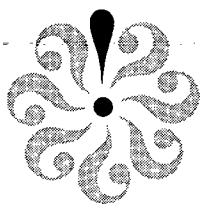
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AERODYNAMIC SHAPE OPTIMIZATION DIRECTED TOWARD A SUPERSONIC TRANSPORT USING SENSITIVITY ANALYSIS

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§.1 Summary

This investigation was conducted from March 1994 to August 1995, primarily, to extend and implement the previously developed aerodynamic design optimization methodologies¹ for the problems related to a supersonic transport design. These methods had demonstrated promise to improve the designs (more specifically, the shape) of aerodynamic surfaces, by coupling optimization algorithms (OA) with Computational Fluid Dynamics (CFD) algorithms via sensitivity analyses (SA) and surface definition methods from Computer Aided Design (CAD).

The present (i.e. conducted under Grant NAG-1-1576) extensions of these methods and their supersonic implementations have produced wing section designs, delta wing designs, cranked-delta wing designs, and nacelle designs, all of which have been reported in the open literature (see §.4). Despite the fact that these configurations were highly simplified to be of any practical or commercial use, they served the algorithmic and proof-of-concept objectives of the study very well.

The primary cause for the configurational simplifications, other than the usual simplify-to-study-the-fundamentals reason, were the premature closing of the project. Only after the first of the originally intended three-year term, both the funds and the computer resources supporting the project were abruptly cut due to their severe shortages at the funding agency.

¹Superscripts indicate reference numbers

Nonetheless, it was shown that the extended methodologies could be viable options in optimizing the design of not only an isolated single-component configuration, but also a multiple-component configuration in supersonic and viscous flow. This allowed designing with the mutual interference of the components being one of the constraints all along the evolution of the shapes.

In the remainder of this report, first an overview of the technical *approach* is presented in §.2; then, a synopsis of the *results* obtained with the support under NAG-1-1576 is given in §.3. The details are available in the technical publications listed in §.4. and sampled by their cover pages in §.5.

§.2 Approach

Aerodynamic design of an aircraft or its components may be performed by one of the numerous approaches being practiced today. Computationally, however, the approaches are either done by an *inverse* method or a *direct* method. Although each has its own merits, the direct numerical optimization methods enjoy the advantage of working towards an easily identifiable objective without the need to specify any *target* designs or shapes. Specifying such targets requires a database, which may not always be available, particularly, for complex configurations with aerodynamically interfering components.

The accuracy of the optimization method in search of better designs and the efficiency with which it can accomplish this, are directly related to the accurate and efficient receipt of the *gradient information* on the objectives and the constraints; that is, the sensitivity coefficients. This has been the differentiating factor between the many direct optimization approaches currently being studied.

Sensitivity coefficients can be delivered to the optimizer through *sensitivity analysis*, which often refers to the quasi-analytically obtained sensitivities, rather than the traditional finite-differences (brute-force) approach. To this end, the governing equations of fluid flow can be differentiated analytically either by starting with their original differential form and using the variational concepts² (*variational* sensitivity analysis, which is also known as either continuous method, or adjoint formulation, or control theory approach), or after they have been CFD-discretized (*discrete* sensitivity analysis)³.

The present extensions and their supersonic implementations were for a *direct* method: a *gradient-based* optimization method using the *quasi-analytical* sensitivity analysis for the *discrete* sensitivities, that consisted of the following components⁴⁻¹²:

- (1) *formulation* of the objective function, and the aerodynamic and geometrical constraints;
- (2) geometrical *parameterization* and redefinition of shapes and configurations;
- (3) generation and *regeneration* of surface and volume *grids*;
- (4) surface *grid sensitivities* and the *volume-grid-to-surface-grid* relation;
- (5) computational fluid dynamics (CFD) or other approximate^{4,5} methods for *analysis* ;
- (6) gradients of the objective function and the constraints with respect to the design variables - (*sensitivity coefficients*);
- (7) gradient-based *optimization* algorithm;
- (8) gradients of the optimized shape to the design invariants or parameters - (*sensitivity derivatives*).

Components of Aerodynamic Shape Optimization

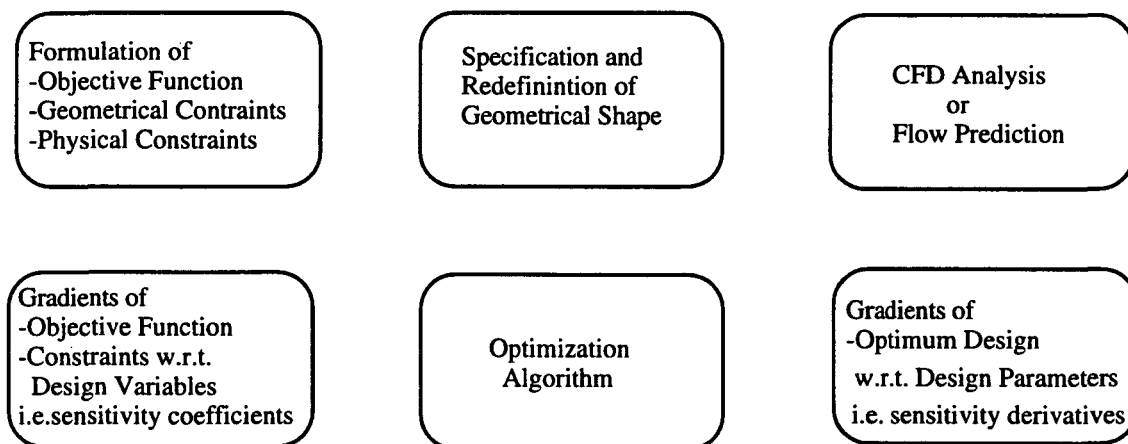


Figure 1.

The present flow analyses were performed either by the computer code CFL3D,¹³ or the code AeSOP¹ developed under the Grant NAG-1-1188, or the approximate flow prediction method.^{4,5} The optimization code was the ADS¹⁴ computer code. The rest of the components shown in Fig. 1 were developed under the Grant NAG-1-1188.

§.2 Synopsis of Results

In addition to the essential algorithmic developments, of the intended (for the three-year period) implementations those that were completed during this period are the following:

- (1) optimizing the shape of an isolated conical **nacelle** with and without the viscous effects¹⁵;
- (2) optimizing the **nacelle** shape in the proximity of a **flat plate wing** (wing interference on the nacelle shape)¹⁵;
- (3) optimizing the shape of an isolated **delta wing**^{16,17} for natural flow¹⁸;
- (4) optimizing the shape of an isolated **cranked delta wing**^{16,17};
- (5) optimizing the shape of a **normal wing section** with a supersonic viscous leading-edge flow (outboard section of a cranked-delta wing)^{19,20};
- (6) optimizing the shape of a **normal wing section**^{19,20} with a subsonic viscous leading-edge flow (inboard section of a cranked-delta wing in supersonic flow) to exploit the **leading-edge thrust**.²¹

This research has constituted yet another step in developing the methods and computational tools, which require less expertise and less database (no target aerodynamics) in the particular field of their application (e.g. propulsion integration), and much less time of the designer-in-the-loop (automatic optimization); however, they provide more information to the designer (sensitivities, higher order flow equations) more accurately (quasi-analytical sensitivity analysis) and more efficiently (less number of flow analyses).

The products of this research can conceivably be used in the future for the following reasons:

- (1) to guide the supersonic transport model developments for the future wind tunnel tests;
- (2) to guide the future CFD analyses of actual supersonic transport configurations;
- (3) the developed methods can be used for future algorithmic studies in: sensitivity analysis, CFD, optimization, surface geometry definition, and linear algebra;
- (4) the computer codes were written with their "case-dependent" routines isolated and identified, which makes them reusable for applications other than the present ones.

Before closing this section, two more important points should be made. First, as a grant of a research project conducted by an academic team, NAG-1-1576 has also provided financial support, either partially (along with one of the following grants: NAG-1-1188 and NAG-1-

1499) or fully, to a Ph.D. student¹⁷ and a Master's student.²⁰ Second, the results of the present investigation has laid the foundation to a follow-up project currently being supported under another grant (NCC-1-211).

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